Design of novel coil structure for wireless power transfer system supporting multi-load and 2-D free-positioning

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Abstract

In the classical WPT technology, when the load coil and the receiving coil are not aligned, the receiving power will be significantly reduced. In this paper, a new type of receiving coil named spiral add planar (SAP) coil is proposed, which can make the receiving power of the load coil almost independent of its position. The T-type equivalent circuit analysis method is used to analyze the transmission performance of the WPT system. By calculating the mutual inductance between non-coaxial coils, it can be proved theoretically that when the load coils are located at different positions, the mutual inductance between the SAP coil and the load coil is more stable comparing to the spiral coil or the planar coil. In addition, this SAP coil can support multiple loads and arbitrary movement of the load within the area of the SAP coil. This paper also proposed the concept of radius ratio (that is, the ratio of the radius of the load coil to the radius of the RX coil), and found that when the radius ratio is less than 1/2, the free-positioning characteristic is good. The simulation and experimental results show that when the load coil moves within the range of the SAP coil, the volatility of its S21 value is less than ± 1 dB.

Keywords WPT · Free-positioning · SAP coil · Radius ratio

1 Introduction

The wireless power transfer (WPT) system is sensitive to the relative position between the transmitting and receiving coils, which means that the transmission performance will get worse when it is misaligned laterally [1]. As a result, the user cannot totally freely charge his mobile phone or wearable devices, while sitting at the table [2]. These problems have largely limited the scope of application of WPT.

In order to achieve free-positioning, it is necessary to have as high a misalignment tolerance as possible between the coils [3]. The double winding coil of Tai Chi form is used, but it has the phenomenon of magnetic field zero point [4]. In addition to solving misalignment tolerance, the input voltage or phase shift angle of the primary side is adjusted to reduce the influence of the mutual inductance change caused by the coil offset on the system output, but it has higher requirements for the detection accuracy and real-time performance of the secondary side feedback signal [5]. In reference [6], the two structures with opposite changing trends are combined to form a hybrid topology resonance structure, but it only has the ability to resist offset in one direction. The relative position of the transmitting coil and the receiving coil is mechanically calibrated through the sensing coil and

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the two-dimensional moving device, however, the additional auxiliary alignment mechanism occupies a large space, the system complexity is high, and the cost is high [7].

The omnidirectional WPT system, which can generate a controllable rotational magnetic field pointing to the load, has attracted much attention in recent years [8, 9]. An omnidirectional WPT system comprising a transmitter with three orthogonal coils has addressed [10–18].

These design methods will cause an increment in the number of active components to operate the system, or prevents user from installing the system in a comfortable position due to their huge volume structure. In order to save volume, Han [19] proposed a receiving (Rx) coil with only two coils, which enables omnidirectional WPT for any type of transmitting (Tx) system. However, the above studies require ferrite core.

In consumer electronics applications, such as bluetooth earphones and wearable devices, the device is usually charged by placing it on the table. Therefore, it is more necessary to achieve 2-D free-positioning in a certain area than 3-D flexibility [20]. In the receiving device, a small planar or spiral coil is preferred as the load coil.

In addition, most omnidirectional WPT systems use a two-coil structure (transmitting coil and receiving coil) [21–23]. In the traditional magnetic-coupled resonant wireless power transfer (MCR–WPT) system, compared with the two-coil structure with shorter transmission distance, the four-coil (source coil, transmitting coil (TX), receiving coil (RX), and load coil) structure has a good transmitting distance with high efficiency. This four-coil structure can be extended with free-positioning characteristics.

In this paper, an improved receiving coil design is proposed by combining the structures of a spiral coil and a planar coil (named SAP coil). The SAP coil structure is mainly used for the RX coil among the four coils. In the actual environment, the source coil and the TX coil are buried in the ground without any changes, and the SAP coil is used as the RX coil on the desktop, and the wearable device and small radius load on the desktop can achieve free-positioning during the charging process. When the load coil with a small radius moves in the area of the receiving coil, the efficiency of the WPT system is almost unchanged. Multiple loads can be placed on the SAP coil, and the receiving efficiency between multiple loads is almost unchanged. A new concept

Fig. 1 Schematic of a magnetic coupling system

“radius ratio” is proposed, which has an important influence on the characteristics of free-positioning.

2 Circuit analysis of WPT

2.1 Theoretical modeling of the WPT system

A typical WPT magnetic coupling resonance system consists of a high-frequency power supply, source coil, TX coil, RX coil, and load coil (shown in Fig. 1). V_{S1} is the AC current source, and Z_s is the internal resistance of the AC current source. $C1$, $C2$, and $C3$ are the matching capacitances of the source coil, the TX coil, and the RX coil, respectively. R_{S1} , R_{S2} , R_{S3} and R_{S4} are the parasitic resistances of each coil. R_{L1} is the load resistor. $M12$ is the mutual inductance between the source coil and the TX coil, $M23$ is the mutual inductance between the TX coil and the RX coil, and $M34$ is the mutual inductance between the RX coil and the load coil. The source coil is close to the TX coil, and the load coil is close to the RX coil.

In the working process of this system (Fig. 1), only $M34$ will change, so the circuit is simplified as shown in Fig. 2. The circuit diagram obtained by the replace transformer with the T-type network is shown in Fig. 2.

A simplified circuit (Fig. 3) is obtained by using the Norton theorem to convert the left part of the circuit into a source (V_{s3}) and an impedance (Z_{s3}).

In Fig. 3, V_{s3} can be expressed as

$$V_{s3} = \frac{-\omega^2 LM_1 LM_2}{(Z_s + Z_1)(Z_2 + j\omega LM_2) - \omega^2 LM_1 LM_2 + (Z_s + Z_1 + Z_2)j\omega LM_1} V_{s1} \quad (1)$$

Since the mutual inductance between the coils is reciprocal, the mutual inductance between the RX coil and the load

Fig. 2 Schematic diagram of the system after the T-type equivalence

Fig. 3 Circuit diagram simplified by NORTON's theorem

coil (M_{34} and M_{43}) is marked as M . Using Kirchhoff's law, the following equation can be obtained.

$$\begin{cases} V_{s3} = Z_{T3}I_3 + j\omega MI_4 \\ 0 = Z_4I_4 + j\omega MI_3 \end{cases} \quad (2)$$

I_3 and I_4 can be obtained as follows:

$$I_3 = \frac{Z_4 V_{s3}}{Z_{T3}Z_4 + (\omega M)^2}, I_4 = \frac{-j\omega M V_{s3}}{Z_{T3}Z_4 + (\omega M)^2}. \quad (3)$$

The output power of V_{s3} is calculated as

$$P_{in} = \frac{(Z_{s5}[(R_{s4} + R_{L1})^2 + X_4^2] + \omega^2 M^2(R_{s4} + R_{L1}))V_{s3}^2}{[Z_{s5}(R_{s4} + R_{L1}) - X_3X_4 + \omega^2 M^2]^2 + [Z_{s5}X_4 + (R_{s4} + R_{L1})X_3]^2} \quad (4)$$

where $X_3 = \omega L_3 - \frac{1}{\omega C_4}$, $X_4 = \omega L_4$.

The consuming power of R_{L1} is given as follows:

$$P_O = \frac{(\omega M)^2 V_{s3}^2 R_{L1}}{[Z_{s5}(R_{s4} + R_{L1}) - X_3X_4 + \omega^2 M^2]^2 + [Z_{s5}X_4 + (R_{s4} + R_{L1})X_3]^2} \quad (5)$$

The system efficiency can be calculated.

$$\eta = \frac{\omega^2 R_{L1}}{\frac{Z_{s5}[(R_{s4} + R_{L1})^2 + X_4^2]}{M^2} + \omega^2 (R_{s4} + R_{L1})} \quad (6)$$

That is to say, when the parameters of coil are certain, increasing M increases η , though other parameters also influence η , M is the quadratic of η , which has a greater impact on it.

2.2 Calculation of the mutual inductance

In this four-coil system, the source coil and TX coil remain unchanged. The RX coil will change in structure, and the load coil will change in its position, the mutual inductance (M_{23}) between TX coil and RX coil will not change with the change of RX coil structure. The number of turns of the RX coil (spiral coil, planar coil or SAP coil) is adjusted to make M_{23} unchanged. So only, the mutual inductance (M_{34}) between the RX coil and the load coil needs to be investigated.

The schematic diagram of the non-coaxial parallel state of the load coil and the RX coil is shown in Fig. 4. t is the radial distance between the load coil and RX coil, and h is the axial distance between the two coils. r_1 is the radius of load coil, and r_2 is the radius of RX coil. N_1 and N_2 are the turns of load coil and RX coil, respectively. The coordinate of the center of the load coil is (x, y, z) , and the coordinate of the center of the RX coil is $(0, 0, 0)$.

Fig. 4 Position relation of non-coaxial coil

The mutual inductance between load coil and RX coil can be expressed as follows:

$$M = \frac{\mu_0 N_1 N_2}{4\pi} \iint \frac{r_1 r_2 \cos(\theta - \varphi) d\theta d\varphi}{\sqrt{(r_1 \cos \theta - r_2 \cos \varphi)^2 + (r_1 \sin \theta + t - r_2 \sin \varphi)^2 + h^2}} \quad (7)$$

MATLAB was used to calculate the mutual inductance, and the parameters were set as $r_1 = 2.5$ cm and $r_2 = 15$ cm (RX coil is much bigger than load coil). The radial distance t increase from 0 to 20 cm in the steps of 2 cm, which means that load coil moves from the center to the edge of RX coil in the radial direction. The axial distance parameter $h = 2$ cm. The spiral coil is applied to the load coil. RX coil has three different structures: spiral coil, planar coil, and SAP coil, respectively (shown in Fig. 5a). While load coil moves radial on RX coil, the value of the mutual inductance M between the load coil and the RX coil (spiral coil, planar coil, and SAP coil, respectively) is calculated with Eq. (7). The calculation result is shown in Fig. 5b.

If RX coil is a spiral coil, the mutual inductance M will gradually increase as the load coil moves from the center to the edge of RX coil. And when the radial distance is greater than 12 cm, the mutual inductance drops sharply.

If RX coil is a planar coil, the mutual inductance M is strong when load coil is located at the center of RX coil, and the mutual inductance is weak at the edge of RX coil.

If the SAP coil is used for RX coil, the mutual inductance M is not sensitive to the movement as the radial distance is less than 12 cm.

Furthermore, since mutual inductance M is much stable when the SAP coil is adopted, the efficiency of the WPT

Fig. 5 Mutual inductance calculated by MATLAB. **a** Three different structures of RX coil. **b** The calculated value of the mutual inductance M

system changes much less, while the load coil moves in the range of SAP coil according to Eq. (6). Meanwhile free-positioning can also be achieved when the SAP coil is used in a two-coil system.

In this paper, factors which directly affect coil transfer efficiency are analyzed first. It is concluded that by directly changing the mutual inductance by changing the coil structure, the efficiency can be indirectly affected. Therefore, in order to study the free positioning of the coil, the SAP coil with the above characteristics was built. The performance comparison was made with different structural coil, respectively, through simulation and experiment in the following chapters.

3 Simulation and parameter optimization

3.1 Simulation process

In this paper, HFSS and Designer are used for joint simulation. First, the coil model is drawn in HFSS, as shown in Fig. 6a. Then, the HFSS coil model is imported into the Designer software. The impedance matching circuit is shown in Fig. 6b. The S parameters were obtained by Designer

Fig. 6 HFSS coil model and Designer model. **a** The model of the coil in HFSS. **b** The model in the Designer software

software simulation. In this paper, the S21 parameter is the gain from the source coil to the load coil.

As shown in Fig. 6a, the improved coil (SAP coil) is used as the receiving resonance coil (RX). In this paper, the power level of all simulated source coil ports is 1 W. In the WPT system, the transmission distance of cm-m can be achieved by letting the TX coil and the RX coil work at the MHz frequency. So the resonance frequency is 2 MHz. The distances of each part of the coil are set as follows: the distance between the source coil and the TX coil is 2 cm, the distance between the TX coil and the RX coil is 30 cm, and the distance between the RX coil and the load coil is 2 cm. All coils were made of copper wires with a wire diameter of 2 mm.

3.2 Comparison of different structures of the RX coil

The efficiency of the WPT system is investigated when the RX coil is spiral coil, planar coil, and SAP coil, respectively. The structural parameters of the three type RX coils

Table 1 Coil parameters of different structures (the turns spacing of SAP side is 0.5 cm and the turns spacing of SAP bottom is 2 cm)

	Inner radius of Planar coil (cm)	Outside radius of Planar coil (cm)	Number of turns	Turns spacing (cm)
Spiral coil	–	15	6	0.5
Planar coil	1	15	14	1
SAP coil	7	15	9	0.5/2

are shown in Table 1. When the RX coil is spiral coil, planar coil and SAP coil, respectively, the mutual inductance (M23) between the TX coil and the RX coil remains unchanged. The simulation result of S21 is shown in Fig. 7. The spiral load coils with a radius of 2.5 cm (Fig. 7a) and SAP load coils a radius of 2.5 cm (Fig. 7b) move radially on the RX

coils of three different structures. It can be seen that the S21 value of the SAP coil (as RX coil) has less volatility, while the load coil is moving outward along the radial direction from the center of the RX coil.

In addition, because of SAP load coil has more turns, so the SAP load coil with a radius of 2.5 cm receives more power than the SAP load coil with the radius of 2.5 cm. Their S21 trends are the same when the load coils of different structures with small radius move radially on the RX coils of three different structures.

3.3 Optimization of SAP coil structural parameter

3.3.1 Optimization of spiral coil radius in the SAP coil

The SAP coil can be divided into two parts: spiral coil (on the side of SAP) and planar coil (on the bottom of SAP). In this part, the radius of the spiral coil is optimized when the planar coil parameters were fixed. The parameters of the planar coil are: the inner radius is 1 cm, the outer radius is 15 cm, and the turns spacing is 2 cm. The radius of the spiral load coil is 2.5 cm. The simulation results are shown in Fig. 8.

In Fig. 8, when the radius of the spiral coil is small (5 cm), the S21 value is higher when the load coil at the center of the RX coil; however, when the load coil is located away from the center of the RX coil, the S21 value is significantly poor. When the radius of the spiral coil increases, although the S21 value at the center of the RX coil is slightly worse, S21 value can be obviously improved at a certain distance from the center of the RX coil. When the radius of the spiral coil is 15 cm, the volatility of S21 value is less than 5 dB when the load coil moves in the whole RX coil. Therefore, the radius of the spiral coil is selected as 15 cm.

Fig. 7 Radial load coil movement on the coils of different structures. **a** When the radius of the spiral load coil is 2.5 cm. **b** When the radius of the SAP load coil is 2.5 cm

Fig. 8 Different radii of the spiral coils in SAP coil

3.3.2 Optimization of the inner and outer radius of the planar coil in the SAP coil

The inner and outer radius, of the planar coil in the SAP coil, are optimized in the condition that the radius of the spiral coil is 15 cm (shown in Fig. 9). In the optimization, the inner radius is adjusted from 1 to 13 cm, and the outer radius is set from the inner radius to 15 cm. The values in Table 2 are obtained by subtracting the minimum S21 value from the maximum S21 value when the load coil moves in the radial direction. The smaller the value, the more stable the S21 value by the load coil from the SAP coil. After comparing the data in Table 2, the inner radius is selected as 7 cm and the outside radius is selected as 15 cm.

4 Performance of WPT system with SAP coil

4.1 Compatibility of radial movement of different load coils

In order to investigate the compatibility of SAP coils, load coils of different structures are used to move radially on the SAP coils. Table 3 shows the parameters of different load coils, and Fig. 10 shows the simulation results of S21. Since the magnetic field near the SAP coil is almost

Fig. 9 SAP coil diagram

Table 2 S21 difference of the inner and outer radius of the planar coil in the SAP coil. (a) Outside radius (cm). (b) Inner radius (cm)

b	a						
	3	5	7	9	11	13	15
1	14.8	8.9	9.27	5.54	5.300	4.98	5.31
5	–	–	3.7	3.8	6.65	5.12	2.71
7	–	–	–	6.07	1.33	1.50	1.12
9	–	–	–	–	4.26	5.12	1.90
13	–	–	–	–	–	–	5.65

Table 3 Parameters of different structural load coils (the turns spacing of SAP load coil side is 0.5 cm and the turns spacing of SAP load coil bottom is 0.4 cm)

	Load type	Inner radius (cm)	Outside radius (cm)	Number of turns	Turns spacing (cm)
Load 1	Spiral	–	5	5	0.5
Load 2	Spiral	–	2.5	5	0.5
Load 3	Planar	2.5	5	5	0.5
Load 4	Planar	0	2.5	5	0.5
Load 5	Planar	0	5	5	1
Load 6	SAP	1	5	10	0.5/0.4

uniform, no matter what kind of load coil is applied, it can receive stable power, while moving on the SAP coil. The larger the load coil is, the more power it receives.

4.2 Influence of radius ratio on the S21 by the load coil

It has been found that the radius ratio between load coil and RX coil (radius ratio) plays an important role to maintaining a small volatility mutual inductance. Supposing that radius ratio is α , which means $r_1 = \alpha r_2$.

In order to investigate the influence of the radius ratio, several spiral load coils with different radii are applied in the WPT system with SAP coil. Figure 11 shows the simulation result. The radius are all less than 7 cm (the radius ratio is less than 1/2), and S21 value is almost flat during the load coil moving on the SAP coil. On the contrary, the radius are all greater than 7 cm (the radius ratio is greater than 1/2), and S21 value is not such stable. Then, it is better to make the radius ratio less than 1/2 to keep the S21 value by the load coil independent of the radial distance. The large radius load coil cannot achieve free-positioning because the radial movement of the large radius load coil will cause the M_{34} to drop.

Fig. 10 Trends of load coils with different structures in SAP coils

Fig. 11 The maximum S21 difference of load coils with different radii at different positions

4.3 Multi-load performance of SAP coil

Whether the SAP coil can support multi-load is investigated. In this section, the number of load coil increase from 1 to 4. S21 value in one load coil is shown in Fig. 12.

It can be seen from Fig. 12 that as the number of load coils increases, the S21 value by each load coils decreases.

4.4 Performance of the multi-load coil in motion

It is necessary to investigate that whether SAP coil can support multiple coils to move arbitrarily within the scope of SAP, and whether the movement has an influence on the S21 value by the coils. Several simulations are carried out on this concept.

Fig. 12 Gradually increase the number of load coils on the SAP coil platform

Firstly, two load coils with the same radius of 2.5 cm are placed on the RX coil surface, one of the load coils moves in the circumferential direction, and the other one is fixed in one position (shown in Fig. 13a,b,d,e). When SAP is used as the RX coil, the S21 value by the two load coils is independent of position, the S21 value of the two load coils is equal. When the spiral coil is used as the RX coil, the S21 value of the load coil is related to the distance of the load coil from the center (the closer to the center of the spiral coil, the less the receiving capacity). In both cases, when the coil moves in the circumferential direction, the volatility of S21 value is similar. (shown in Fig. 13c,f).

Secondly, the receiving efficiency of two load coils with different radius is evaluated. Compared with Fig. 13, the simulation shown in Fig. 14 only changes the radius of Load 1, and other conditions remain unchanged. Figure 14a, b show the simulation results. It is can be seen that the S21 value by the load coil on the SAP coil is slightly higher than those on the spiral coil, and the large load coil receives more power.

Thirdly, the movement of the load coil in the radial direction is considered. In Fig. 15, the radius of load1 is 5 cm and the radius of load2 is 2.5 cm. When load1 is fixed on the side of the RX coil, load2 moves in the radial direction. A spiral coil and an SAP coil are used as the RX platform, respectively (shown in Fig. 15a, b). The simulation result is shown in Fig. 15c. As the RX coil is SAP coil, the S21 value by load1 and load2 changes little, while the load2 is moving. On the contrary, the S21 value by load1 and load2 changes much, while load2 is moving if the spiral coil is RX coil.

According to the simulation results shown in Figs. 13, 14 and 15, it can be concluded that SAP coils are superior to the spiral coils in supporting the mobility of the load coils.

Fig. 13 Schematic diagram and simulation results when load1 and load2 with same radius moving circumferential direction. **a** On the SAP coil, load2 moves in the circumferential direction at a position 9 cm away from the center of the RX coil. **b** On the spiral coil, load2 moves as described in **a**. **c** Simulation results while load2 is at posi-

tion 9 cm away from the center of the RX coil. **d** On the SAP coil, load2 moves in the circumferential direction at a position 12 cm away from the center of the RX coil. **e** On the spiral coil, load2 moves as described in **d**. **f** Simulation results while load2 is at position 12 cm away from the center of the RX coil

5 Experiments

In order to verify the correctness of the theoretical analysis for the influence of the radial distance and the coil radius ratio on the SAP coil transmission efficiency as well as the improvement effect, we designed and tested the experimental platform of the WPT system. Table 4 shows the specific parameter design. Before the experiment, the inductance and parasitic capacitance of the coil were measured with the inductance–capacitance–resistance meter, and the average value of multiple measurements was obtained.

The system is shown in Fig. 16. The experimental platform is mainly composed of Vector net measuring instrument, a source coil, a TX coil, a RX coil (SAP coil), and load coil. The parameters of the various coils in the experimental system are consistent with the various parameters of the coil model in the simulation and in the theoretical model (including the turns spacing, wire diameter, distance between TX coil, and RX coil, etc.). In the experiment, the power level of the source coil port is 1 W. Using compensation capacitors, the resonance frequency is 2 MHz. The TX coil resonates with the RX coil, and the load coil receives power from the RX coil. In the experiment, the load resistance is 200 Ω .

Figure 17 shows the different types of loads. The parameters of the manufacturing coil are the same as those of the simulation coil (see Table 3).

5.1 Experimental verification of SAP coil design

Figure 18 shows the radial distance movement of Load2 in the spiral coil, planar coil, and SAP coil. The experiment results are consistent with the theoretical analysis and simulations results. The transmission efficiency of the SAP coil has less volatility than the spiral or the planar coil. In conclusion, the SAP coil combines the advantages of the spiral coil and the planar coil, and can realize the free positioning of the load coil in the radiation area of the RX coil.

Figure 19 shows the experimental results obtained for the radial distances of different types of load coils in SAP coils. The S21 value of the different types of load coils on the SAP coil is uniform and stable (i.e., free-positioning). Due to the different structures, the S21 value is also different.

Fig. 14 Simulation results when load1 (with the radius of 5 cm) and load2 with different radius moving circumferential direction. **a** Simulation results while load2 is at position 9 cm away from the center of the RX coil. **b** Simulation results while load2 is at position 12 cm away from the center of the RX coil

5.2 Verification of the influence of radius ratio

Multiple load coils with different radius (2–12 cm) are applied to the WPT system with SAP coil as the RX coil. The experimental results shown in Fig. 20 are consistent with the simulation results (Fig. 11). It can be concluded that the free-positioning characteristic can be obtained when the radius ratio is less than 1/2.

5.3 Experimental results of multiple load coils

Firstly, a multi-load experiment was carried out, and the same load was carried out 4 times in total. In the experiment, the number of load coils gradually increased in the SAP coil, and the S21 value change of each load was observed.

Fig. 15 Schematic diagram and simulation results when load1 is fixed and load2 moves in the radial direction. **a** The SAP coil is used as RX coil. **b** The spiral coil is used as RX coil. **c** Simulation results

Table 4 Component parameters in the system

Parameter name	Value
Source resonant capacitance	1.2 nF
Transmitting resonant capacitance	621 pF
Receiving resonant capacitance	315 pF
Source coil	5.32 uH
TX coil	10.2 uH
RX coil (SAP coil)	20.09 uH
Load 1	0.83 uH
Load 2	2.22 uH
Load 3	0.766 uH
Load 4	1.01 uH

Fig. 16 Experimental setup

Fig. 17 Different load coil structures manufactured as per Table 3

Fig. 18 Anti-offset characteristics of different types of RX coils

Fig. 19 Relationship between the different types of load coils and S21

Figure 21 shows the experimental results. It can be seen that when the number of loads increases from 1 to 4, the S21 value of each coil only drops by less than 4 dB, which is consistent with the simulation results. Therefore, it is known that the SAP coil is good at supporting multiple loads to work simultaneously.

Fig. 20 Relationship between the different radii of the load coil and S21

Fig. 21 Gradually increase the number of load coils on the SAP platform

Secondly, an experiment was conducted to study the effect of load movement on the reception effect. In the experiment, two load forms are used, and one of the coils is moved, while the other is fixed. The specific conditions of the experiment are consistent with the simulation conditions in Sect. 4.4. The experimental results (see Fig. 22) are also consistent with the simulation results.

6 Conclusions

This paper presented a novel design of RX coil (named SAP coil), which is suitable for the 4-coil MCR-WPT system. On the 2D plane inside the SAP coil, it can be realized that the load coil power is independent of the load position. Through

Fig. 22 The experiment results of evaluation of load movement on the receiving performance. **a** Two identical loads, and one load moves in the circumferential direction. (same condition with the simulation of Fig. 3). **b** Two different loads, and one load moves in the circumferential direction. (same condition with the simulation of Fig. 4). **c** Two different loads, and one load moves in the radial direction. (same condition with the simulation of Fig. 5)

the theoretical calculation of the mutual inductance and the equivalent of the 4-coil circuit model, it can be proved that the SAP coil combines the advantages of the spiral coil and the planar coil, so that mutual inductance between the load coil and the SAP coil has little volatility in the range of the RX coil. When the transmission distance and M23 are the same, the volume occupied by the SAP coil is smaller than that of the ordinary spiral coil of the same diameter. And then, it is verified by simulation and experiment that the SAP has better free-positioning than spiral coil and planar, and can support a variety of load coil styles (such as spiral or planar coil). In addition, it is found that when the radius ratio between load coil and the SAP coil is less than 1/2, the free-positioning will be more significant. Both the simulations and experiments results show that SAP can support multiple loads to work simultaneously, and the load can move arbitrarily within the range of the RX coil, and the volatility of the S21 value is less than ± 1 dB.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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